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Ballistic transport of holes and phonon replicas in lightly doped GaAs

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We study the motion of nonequilibrium light holes injected into very lightly doped GaAs using a *hot-hole* three-terminal device. We observe directional multiple longitudinal-optical (LO) phonon emission by the holes. Using transverse magnetic field we observed scattering of light holes into heavy-hole states after the first phonon emission. An unexpected 18 meV shift of the phonon replica spectrum suggests that the Fermi level is pinned in an impurity band, in the gap, formed in the p^+ regions. We find that the mean-free path of light holes, with energy just below the LO phonon emission threshold, is 300–360 nm. The results are compared with those obtained for electrons. [S0163-1829(97)51816-9]

Transport of carriers in high purity bulk GaAs has recently been suggested as means to support quantum interference at high currents and energies,[1] not possible in doped regions. Study of the motion of hot (nonequilibrium) ballistic electrons in such a medium,[1,2] at liquid helium temperature, has shown, as expected, that electrons with excess energy above 36 meV have an exceedingly short mean-free path (mfp), mostly due to emission of longitudinal-optical (LO) phonons. However, below 36 meV the electrons indeed have a rather long mfp (a few micrometers long), argued to be determined mostly by impact ionization of neutral impurities. Studying similar physics of hot-ballistic-hole transport in high purity GaAs and utilizing a *hot-hole device*, led us also to observe directional, multiple emission of LO phonons by injected light holes.[3] The first LO phonon emission scatters the light holes into heavy-hole states. Surprisingly, the observed phonon replica spectrum is shifted by some 18 meV toward higher energies (not observed with electrons). We propose the formation of an impurity band in the energy gap in the p^+ regions to be responsible for this shift.

Our experiments utilized a modified three-terminal hot-hole device,[4] grown by molecular-beam epitaxy on a (311)A GaAs substrate with silicon doping. The energy diagram of a generic structure is shown in Fig. 1 (for clarity we use inverted energy notation). Quasi-mono-energetic hole holes are injected from a p^+-GaAs emitter via a tunnel barrier ($\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ emitter barrier) and pass through a thin p^+ base layer (introduced to enable biasing). Holes that do not scatter and are not collected in the base traverse a relatively thick layer of $p^-(\sim 10^{14}\ \mathrm{cm}^{-3})$ GaAs (drift region) adjacent to the base layer. The ballistic fraction of those are eventually collected over a low potential barrier ($\mathrm{Al}_y\mathrm{Ga}_{1-y}\mathrm{As}$ collector barrier) by the p^+-GaAs collector. To reach the collector hole we must have an *energy component* in the direction normal to the layers, $\varepsilon_\perp = \hbar^2 k_\perp^2/2m$, in excess of the collector barrier height ϕ, with $k_\perp$ the normal component of the holes' wave vector, and m the effective mass. Holes that relax in momentum or energy, in the base or the drift regions, cannot surmount the collector barrier, thus they are reflected and eventually thermalized and collected by the base contact. An important aspect in our experiment is that most of the injected holes are *light* in nature. This is a direct result of the selectivity of the tunneling process with probability proportional to $\exp[-2W\sqrt{2m(\phi_E - E)}/\hbar]$, where ϕ_E is the tunnel barrier height, E the holes' energy, and W the tunnel barrier width. For a mass ratio of heavy to light holes of about 8, we find the tunneling probability of light holes to be many orders of magnitude higher than that of heavy holes for $W = 9$ nm and $\phi_E = 190$ meV. This conclusion is also substantiated with a full interband tunneling calculation.[5]

We investigated the motion of light holes in the drift region by varying the injection energy of the holes (via changing emitter-base voltage V_{EB}) and measuring the fraction of holes that are collected by the collector. Experimentally, we measured the *differential transfer ratio* $\alpha \equiv dI_C/dI_E$, where I_E, I_C are the emitter and the collector currents, respectively (Fig. 2). We used α rather than the *static transfer ratio* I_C/I_E because taking a derivative sharpens the effective energy distribution of the injected holes (it results from the subtraction of two, slightly shifted, bell-like energy distributions). Figure 2 shows α as a function of V_{EB}. The results are similar to those obtained for electrons by Brill and co-workers[1,2] and can be explained in the following way: at small V_{EB} the holes do not have enough excess energy to

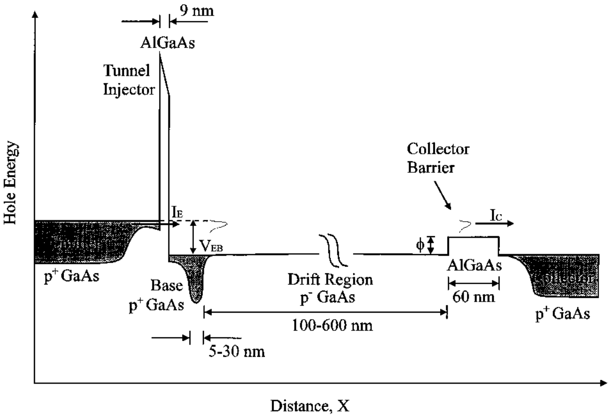

FIG. 1. Schematic energy diagram of the device. The solid line represents the top of the valence band and the gray areas represent the Fermi sea. In this diagram a bias is applied between the emitter and the base leading to injection of holes into the drift region. Energy axis is inverted for clarity.

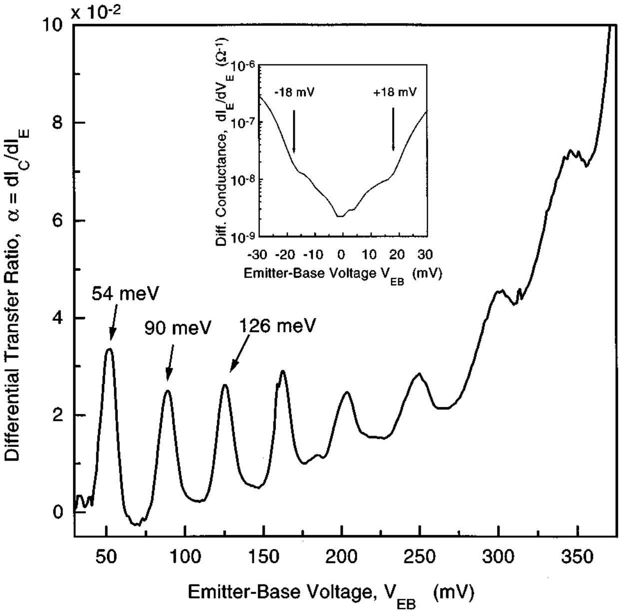

FIG. 2. The differential transfer ratio, measuring the probability of holes to be collected over the collector barrier, is plotted as a function of the emitter base voltage. The first peak is due to a single LO phonon emission and the higher-order peaks are phonon replicas due to multiple LO phonon emission. The phonon replicas spectrum is shifted by 18 mV. The inset shows the two shoulders observed in the differential conductance of the tunnel injector at $V_{\mathrm{EB}}\cong\pm 18$ mV.

surmount the collector barrier and, therefore, $I_B=I_E$ and α equals zero. When $eV_{\mathrm{EB}}\geqslant\phi$, the holes that did not relax in the base or in the drift regions, surmount the collector barrier; I_C increases, and α becomes nonzero. Due to the finite width of the holes' energy distribution, determined by the tunneling process and possible elastic scattering of the holes, increasing V_{EB} further allows more holes to reach the collector and α increases. A maximum in α is reached just before an injected hole has enough excess energy to emit a single LO phonon ($\hbar\omega_{\mathrm{LO}}=36$ meV). Note that this process takes place rather quickly; only $\sim 10^{-13}$ sec after injection.[6] The scattered holes have a smaller energy and thus cannot cross the collector barrier, leading to a sharp drop in α. By increasing V_{EB} further, an injected hole, with energy $E>\phi+\hbar\omega_{\mathrm{LO}}$, emits a single LO phonon but still might have enough excess energy to surmount the collector barrier, thus leading once again to an increase in α. This process continues until the injected holes have enough energy to emit two LO phonons; thereafter α drops again. Such behavior repeats itself a few times in our experiment (up to nine times) leading to the observed LO phonon replicas in α. The observation of such a large number of phonon replicas indicates that the LO phonon emission process is very directional,[2] namely, mostly low momentum phonons are being emitted. The super linear increase of α at high V_{EB} is due to the fact that a large fraction of the injected holes do not emit all the phonons they can emit during their time of flight in the drift region, hence contributing to α regardless of their original energy (a model for this increase is described in Ref. 2). Note, that all higher order replica peaks (above the first peak) result from heavy-hole transport—this point will be discussed later.

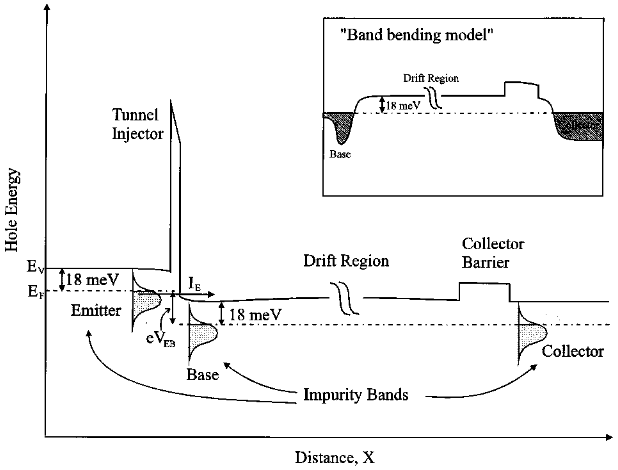

FIG. 3. Band diagram with the suggested *impurity band* model. This model explains the 18 meV shift of the phonon spectrum and the two shoulders in the differential conductance of the tunnel barrier. The inset shows the band diagram of the *band bending* model.

Aside from the distinct directionality after LO phonon emission, observed already for electrons,[4] we find, to our surprise, a shift of some 18 meV in the spectrum of phonon replicas. Instead of having peaks in α at $eV_{\mathrm{EB}}\cong 36n$ meV, where $n=1,2,3\ldots$, we find peaks at $eV_{\mathrm{EB}}\cong 18+36n$ meV. Moreover, the onset of α in Fig. 2, indicating on the height of the collector barrier, is also higher by about 18 mV than expected from the collector barrier height [for $x(\mathrm{AlAs})=0.02$]. Most remarkably, in all the samples we have grown, with different doping levels, different base and drift region lengths, and different barrier heights, the shift of 18 ± 2 meV in the spectrum remained almost unchanged. Furthermore, a two terminal measurement of the differential conductance of the tunnel emitter showed always two distinct shoulders at $V_{\mathrm{EB}}\cong\pm 18$ mV (inset in Fig. 2). This shift strongly suggests that holes are injected at an energy that is some 18 meV lower than expected, with respect to the top of the valence band, namely, their kinetic energy in the drift region is $eV_{\mathrm{EB}}-18$ meV.

Let us discuss this unexpected shift first. A possible reason for this shift might seem, at first sight, a fast band bending near the interface between the heavily doped base and the lightly doped drift region. If $E_F=E_V-18$ meV in the drift region (inset in Fig. 3), then holes are injected into the drift region only when $eV_{\mathrm{EB}}>18$ meV, thus leading to the *18 meV shift*. Indeed, the valence band in the drift region is expected to bend until the Fermi level reaches its bulk position, namely, at the energy of the isolated impurities. Since, the 18 meV shift is observed even with drift region length as small as 100 nm, this band bending, if it exists, should occur on a scale much smaller than this length. However, for our donor compensation $N_d\leqslant 5\times 10^{14}$ cm^{-3} this length should be about ~ 200 nm. Moreover, the 18 meV shift and the width of the replica peaks were found to be independent of the drift region length (from 100 to 600 nm), doping concentration (5×10^{14}–1×10^{17} cm^{-3}), and doping species,[7] implying again that band bending, if it exists, is on a scale much smaller than 100 nm. Note also, that such band bending, cannot offer an explanation for the observed *symmetric* shoulders in the emitter-base tunneling conductance.

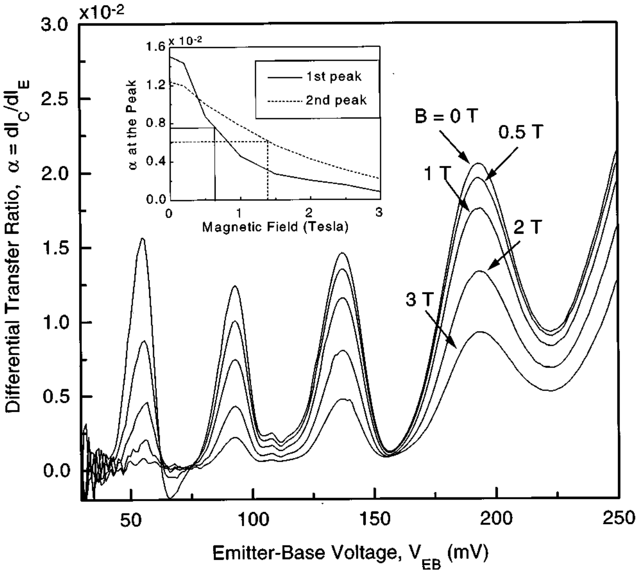

FIG. 4. The effect of normal magnetic field on the phonon replicas spectrum. A fast quench of the first peak and a slower quench of the higher-order peaks is observed. The inset shows the height of the first and second peaks as a function of normal magnetic field. The quenching rates of the first and second peaks can be accounted for by transport of light and heavy holes, respectively.

We propose ''conduction through impurity states'' as a partial explanation for the 18 meV shift. It is usually assumed that a transition from insulator to metal occurs when the impurity band merges with the valence or conduction bands.[8] However, for holes, unlike electrons, the impurity band does not merge easily with the valence band except at very high doping concentrations [above 1×10^{19} cm^{-3} for Be doped GaAs (Ref. 9)]. Suppose the Fermi energy in equilibrium is at E_V-18 meV in the p^+ base and there exists a relatively ''slow'' and unnoticeable band bending in the drift region keeping E_V there aligned with E_V in the base (Fig. 3). In such a case, when $eV_{\mathrm{EB}}<18$ meV, a current can flow into the unoccupied tail of the impurity band in the p^+ base but not into the drift region, since there is no impurity band there. Only when $eV_{\mathrm{EB}}>18$ meV a current can flow into valence-band states in the drift region. The rigid shift in the phonon replica spectrum and in the collector barrier height can thus be accounted for. According to this model, the shoulders in the conductance of the tunnel injector are a direct result of the difference between the density of states in the impurity band and in the valence band in the base region (there might also be a gap in the p^+ regions between the impurity band and the valence band). Unfortunately, this model has its own difficulties. One might argue that the position of the Fermi level in the base should depend on the doping concentration in the base; however, such dependence was not observed. Moreover, it is not clear why higher doping in the drift region did not lead to a faster band bending and ''smearing'' of the replicas. Finally, this model provides no quantitative explanation for the value of the 18 meV shift.

We discuss now the nature of the hot holes. Since the density of states in the heavy-hole band is greater by a factor of ~16 compared to that in the light-hole band, an injected light hole with excess energy larger than the LO phonon emission threshold will lose 36 meV and most probably scatter into the heavy-hole band. A calculation based on Ref. 6 predicts $l\rightarrow h$ scattering rate a few times larger than $l\rightarrow l$ scattering rate at $E\gtrsim\hbar\omega_{\mathrm{LO}}$, but the two scattering rates become similar at higher energies. This is a result of the large momentum transfer needed in the $l\rightarrow h$ transition, inhibiting phonon emission (the Frohlich formula[10]). According to these calculations the first peak in α represents the ballistic motion of light holes and the higher order peaks are due to ballistic motion of heavy holes.

To check the plausibility of this hypothesis, the nature of the traversing holes was tested by applying a magnetic field normal to the direction of hole injection. As the magnetic field is increased a rapid quench of the first LO phonon peak is observed, contrary to a much slower reduction in the height of the higher-order phonon peaks (Fig. 4). This reduction is a direct result of the curved trajectories of the ballistic holes, subsequently arriving at the collector barrier with a smaller component of normal energy, hence, a smaller α. The quench is expected to take place when the cyclotron radius of motion $R_C=\sqrt{2mE}/eB$ is of the order of the drift region length. Taking the magnetic field at which the height of the first peak reduces by a factor of 2 (inset in Fig. 4) and assuming light-hole mass, we find $R_C\cong360$ nm, comparable to the drift region length (300 nm). For the second phonon peak we estimate a similar R_C for a peak reduction by a factor of 2 when a heavy-hole mass is assumed. Note that a light-hole traverses on the average some 30 nm before emitting a LO phonon, a length much smaller than that of the drift region. Extending this approximation to higher-order peaks is not valid anymore because the length traversed before emission of several phonons is not negligible.

How long is the mfp of holes in the drift region? Comparing devices with different base and drift region lengths allows the estimation of the inelastic, or large angle, mfp: $\alpha=\exp[-L_B/\lambda_B]\exp[-L_{\mathrm{DR}}/\lambda_{\mathrm{DR}}]$, where L_B, L_{DR} are the lengths of the base and drift region, respectively, and λ_B, λ_{DR} are the corresponding mfp's. Fabricating devices with $L_B=5-15$ nm and $L_{\mathrm{DR}}=300$ and 600 nm, we find for light holes, at energies just below the LO phonon emission threshold, $\lambda_{\mathrm{DR}}\approx300-360$ nm and $\lambda_B\approx6.5$ nm. The small value of λ_B is not too surprising in view of the fact that the light holes are injected into a very heavily doped base and are scattered by the large population of heavy holes and also by the large amount of ionized impurities. It is interesting to compare the holes' mfp with that of the electrons: Brill and Heiblum[1] found in very lightly doped drift regions that $\lambda_{\mathrm{DR}}(e)=4{,}500$ nm. The much shorter $\lambda_{\mathrm{DR}}(h)$ results mainly from the large final density of states that light holes can scatter into. Brill and Heiblum also argued that the main scattering mechanism for electrons with energies below $\hbar\omega_{\mathrm{LO}}$ is the ionization of neutral impurities in the drift region, rather than Coulomb scattering from ionized impurities; the latter leading only to small angle scattering. If this would be the case in our experiment we would have seen a peak in α at the ionization energy of carbon (at 26 meV). No such peak was observed in any of our experiments, leading to the conclusion that the main scattering mechanism for holes in GaAs below $\hbar\omega_{\mathrm{LO}}$ is not due to impact ionization of impurities. This is reasonable, since the cross section for ionization of a neutral acceptor is relatively small compared to that of a donor (because of the smaller Bohr radius of the acceptor). On the other hand, light holes are likely to scatter *elastically* via ionized impurities into heavy-holes states.[6] The scattering rate of such a process is higher than the rate of light-hole intraband transitions by a factor of ~ 3 (the latter is similar to the scattering rate of electrons via ionized impurities). The holes, in such a process, exchange a large momentum, thus losing directionality and not being collected by the collector.

In conclusion, we have shown that spontaneous emission of LO phonons by hot holes is highly directional. Injected light holes scatter into heavy-holes states via a single phonon emission. An unexpected shift of 18 meV in the phonon emission spectrum indicates pinning of the Fermi level in an impurity band formed in p^+ GaAs, but this observation is not yet fully understood. We have measured the mfp of light holes in lightly doped GaAs below the LO phonon threshold to be $\lambda \approx 300-360$ nm and we argue that the dominant scattering mechanism in this regime is interband elastic scattering via ionized impurities.

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